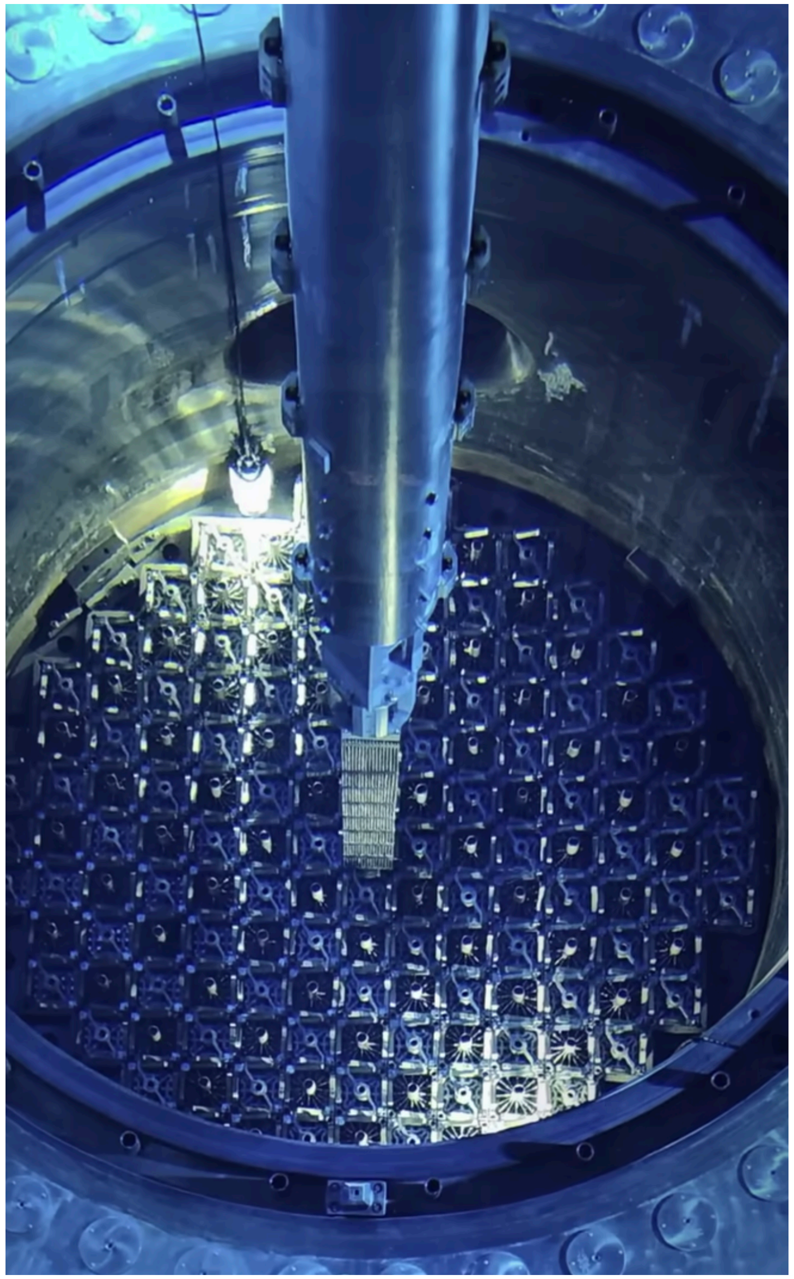
Reactor Neutrinos

P5 Town Hall
March 22, 2023

Bryce Littlejohn
Illinois Institute of Technology

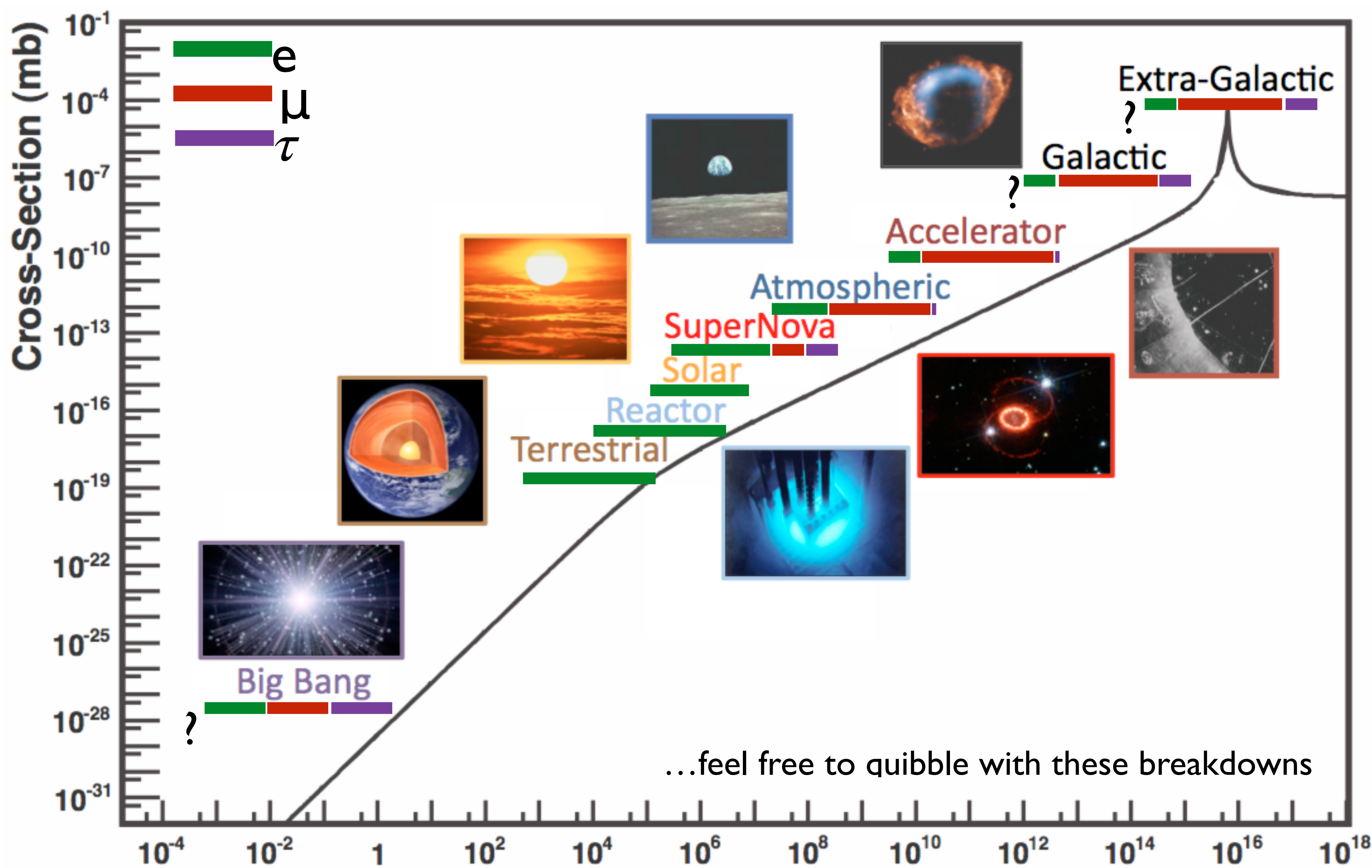


[Commercial Vogtle 3 Reactor: Just Went Critical]

[ORNL's HFIR: Lifetime Extension Plans]
[NIST's NBSR Reactor Just Re-Started]

How Are Reactor Neutrinos Special?

- Energy: MeV-scale, rather than GeV-scale
- Flavor: Pure electron flavor, rather than (mostly) muon flavor
- Operations: terrestrial source operated (paid for) by others
- Attributes belie synergies with accelerator neutrino efforts



Zeller and Formaggio, Rev. Mod. Phys. 84 (2012)

Reactor Neutrinos and P5 Drivers

- **Pursue the physics associated with neutrino mass**
  - Measure oscillation parameters of three Standard Model (SM) neutrinos
  - Probe additional neutrino types via oscillation: sterile neutrinos
  - Appear in Snowmass 2021 as 'NF01' and 'NF02' topical groups

- **Explore the unknown: new particles, interactions, and physical principles.**
  - Using reactors as a laboratory for probing BSM particles (interactions) of low mass (low-energy scale)
  - Developing improved technology and reactor flux models for this enhancing BSM sensitivity
  - Appear in Snowmass 2021 as 'NF03,' 'NF09,' and 'NF10' topical groups

Reactor Neutrinos and P5 Drivers

- **Pursue the physics associated with neutrino mass**

Mass ordering: is the lightest neutrino mostly made of electron flavor?

nos

Lepton flavor: Is the lepton mixing matrix unitary?

- **Explore the unknown: new particles, interactions**

Short-baseline anomalies: Can we see apparent flavor transformation from new mass states/couplings?

w

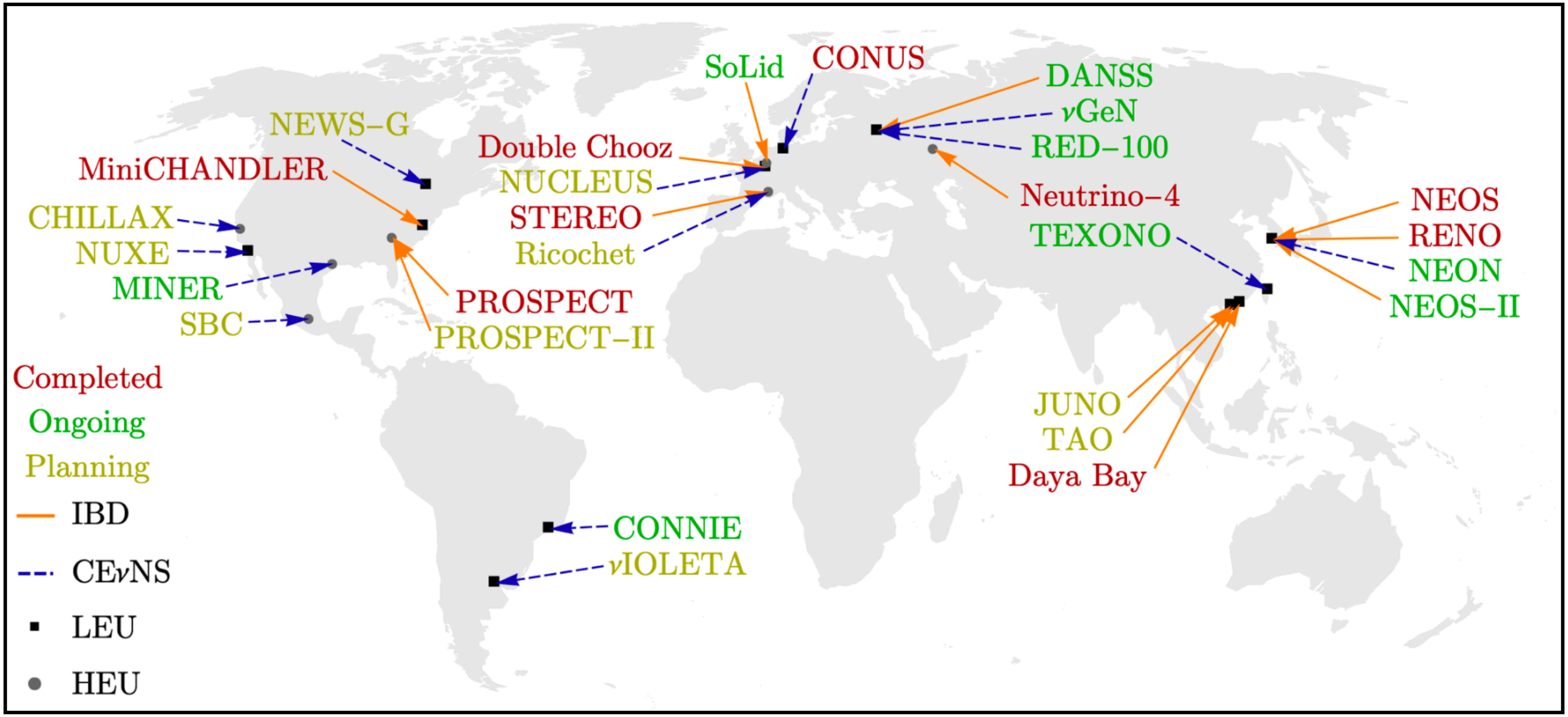
mass (low-energy scale)

Reactors are an essential piece for answering all these open questions.

and ‘NF10’ topical groups

A Diverse Reactor Community

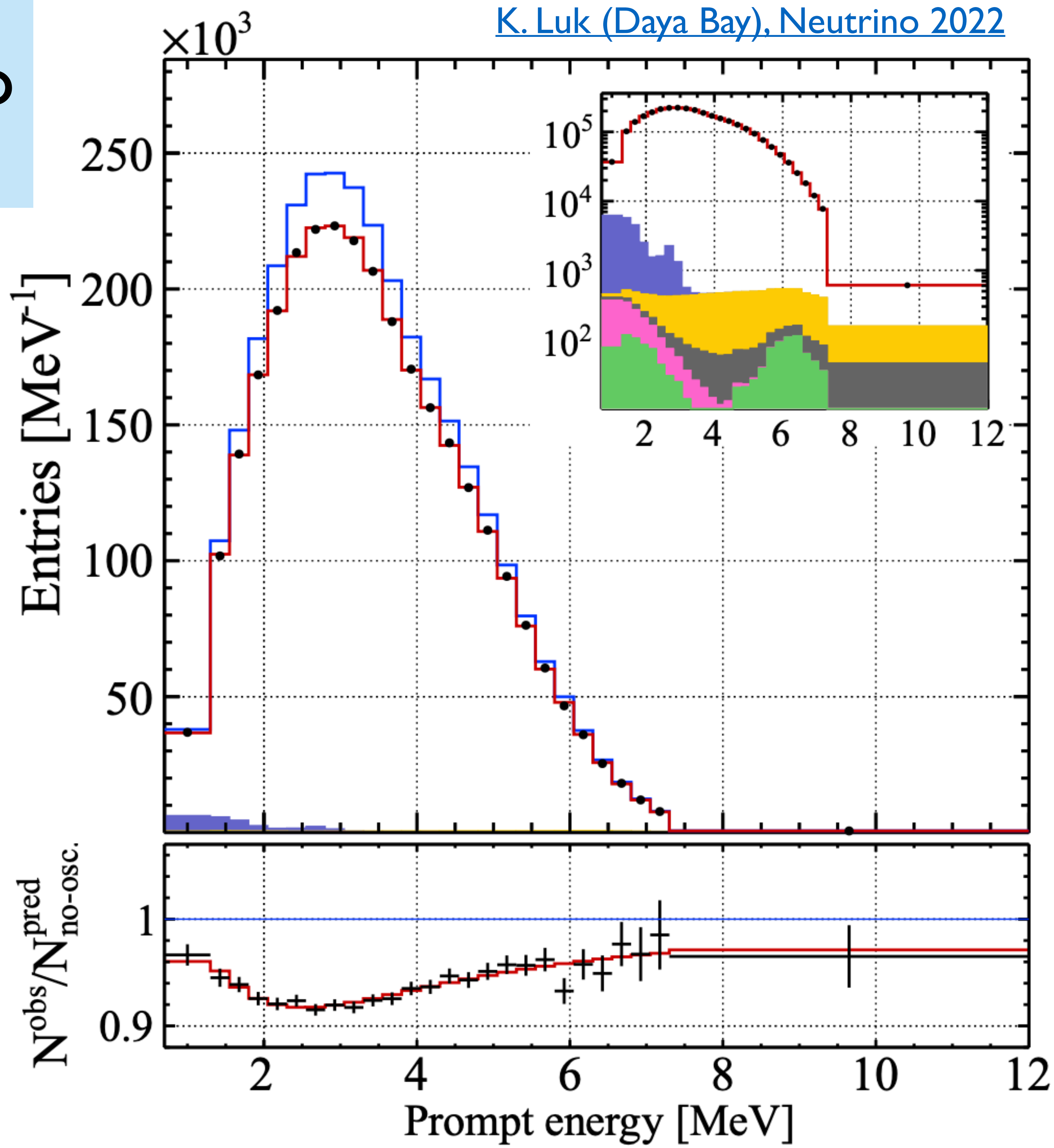
- The reactor neutrino community is a diverse interest group of many experiments with strong relevance to most Topical Groups within the Snowmass 2021 Neutrino Frontier
- During Snowmass 2021, we united to compose a White Paper summarizing the importance of our field to the next decade of particle physics: Akindele et al, hep-ex[2203.07214]



‘Standard’ Oscillations: Progress

- Reactor neutrinos are the source of best precision on some standard model neutrino flavor mixing parameters
- Daya Bay dominates θ_{13} while providing a competitive measurement of Δm^2_{31}
- KamLAND provides world’s best Δm^2_{12} parameter bound

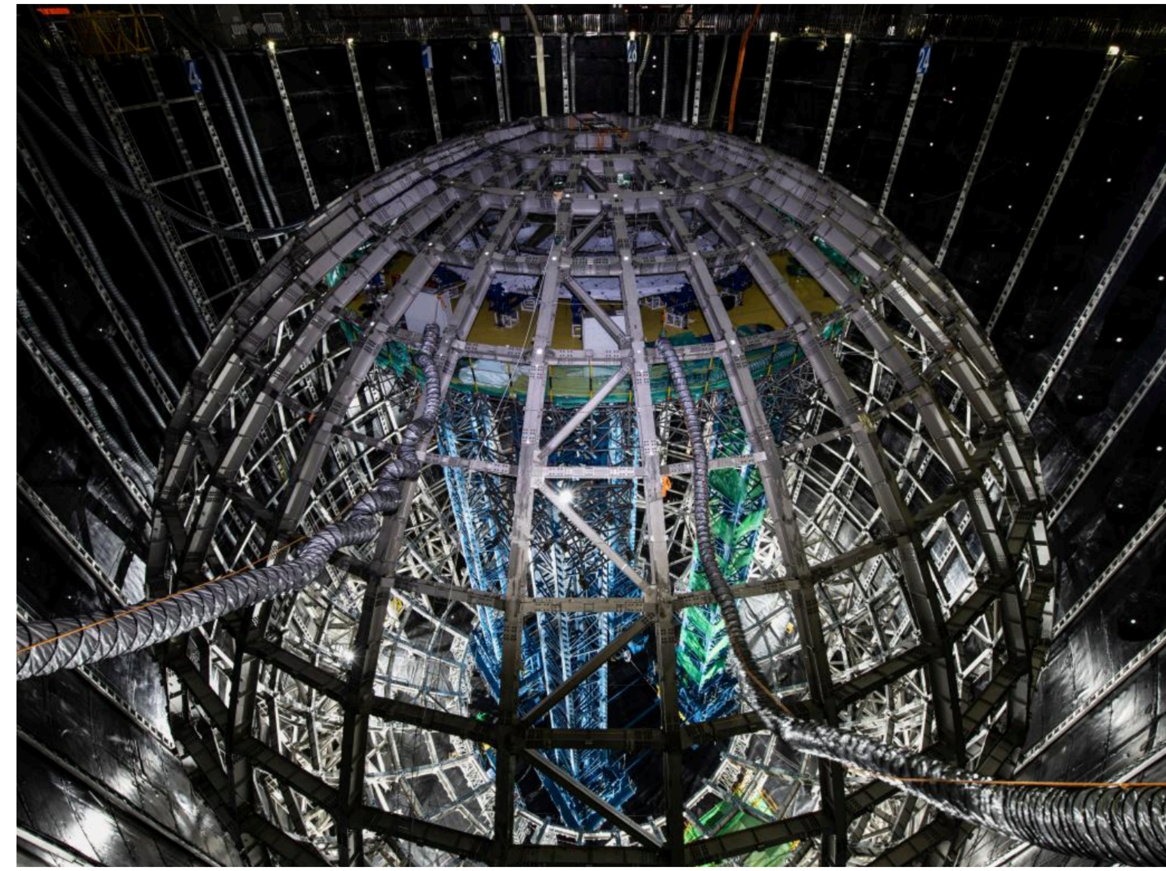
K. Luk (Daya Bay), Neutrino 2022



Standard Oscillations: Future Aims

- JUNO can generate major improvement in θ_{12}, Δm^2_{12}, mass ordering knowledge
  - Detector assembly will be complete at the end of 2023
  - 3σ mass ordering determination expected with six years of data
  - World-best measurements of θ_{12}, Δm^2_{12} in first 100 days
- If we want aspects of lepton flavor mixing to be as well-understood as in the quark sector, reactors are essential.
  - Unitarity tests too: reactors are pure electron-flavor factories, with no matter effects.

Z.Yu (JUNO), IAEA TM (2023)



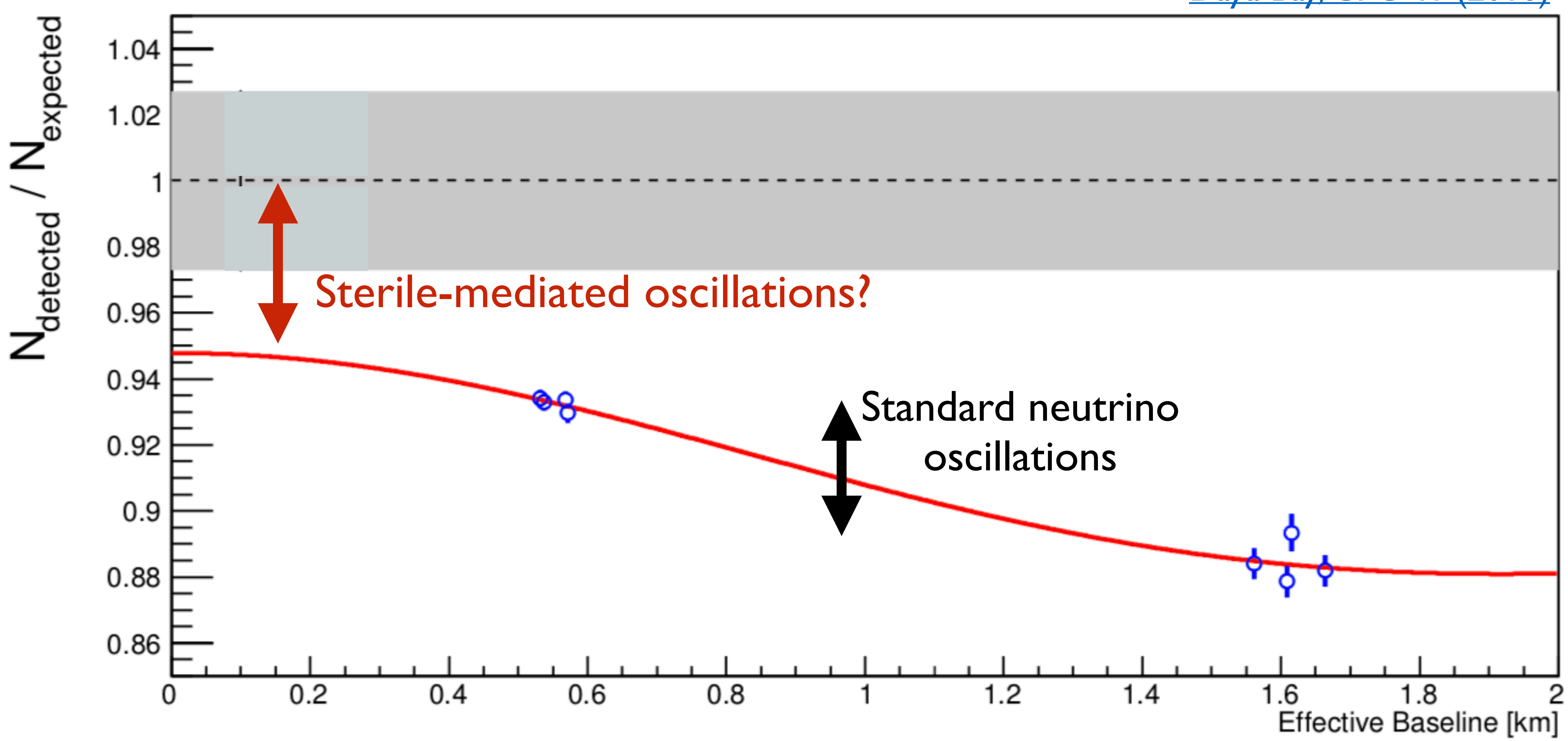
(relat. precision at 3σ)		for quarks
θ_{12}	$(\sim 1\%)$	0.6 %
Δm^2_{21}	$(\sim 1\%)$	
$\|\Delta m^2_{31}\|$	$(\sim 0.5\%)$	
θ_{13}	(9%)	8.3 %
θ_{23}	(24%)	5.2%

T. Schwetz (NuFit), Neutrino 2022

Non-Standard Oscillations: Progress

- Lots of progress in probing the Reactor Antineutrino Anomaly, one of four 'canonical' short-baseline neutrino anomalies

Daya Bay, CPC 41 (2016)



Non-Standard Oscillations: The 'RAA'

- Lots of progress in probing the Reactor Antineutrino Anomaly, one of four 'canonical' short-baseline neutrino anomalies

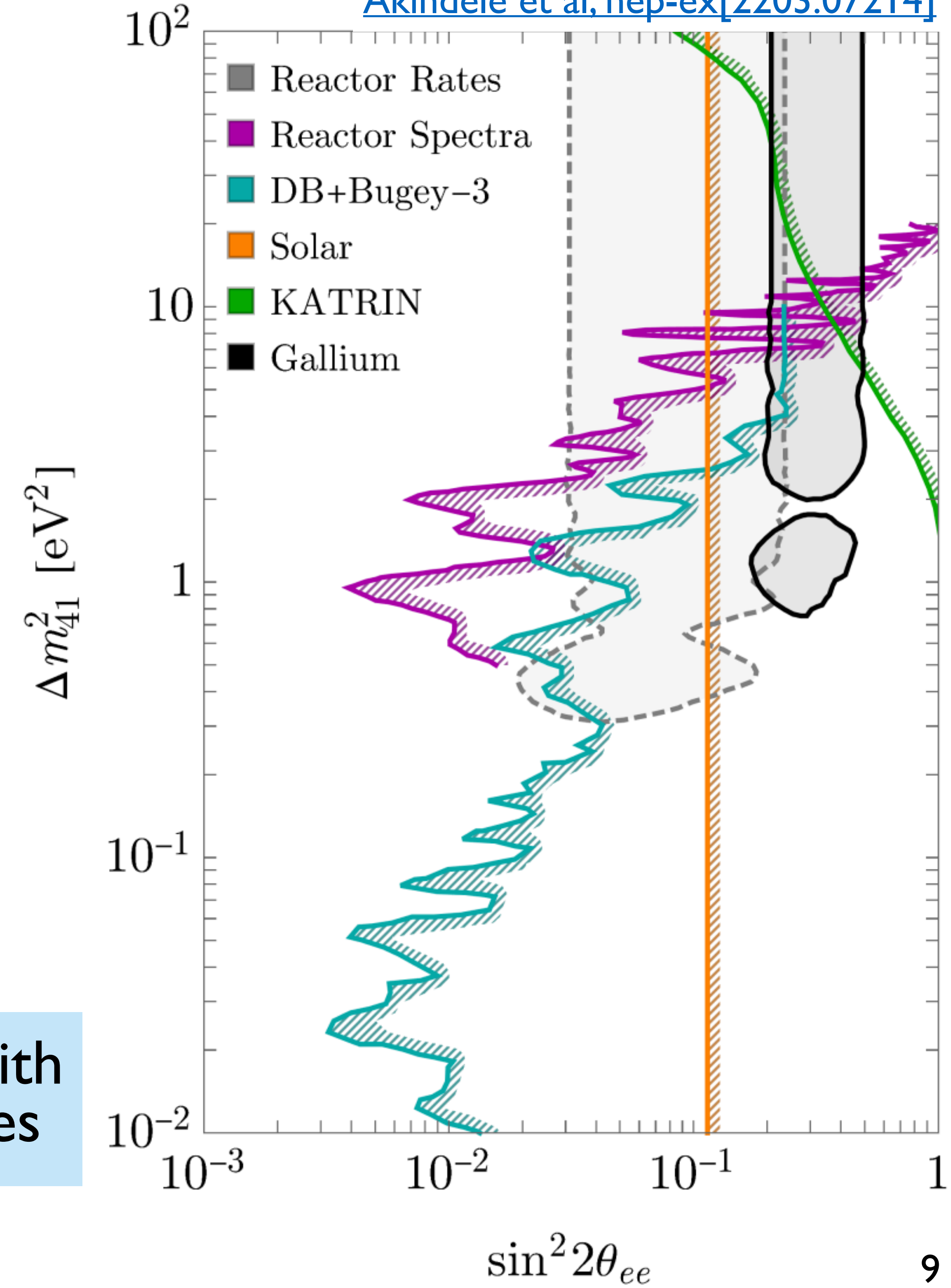
- New experiments (PROSPECT-I, STEREO, NEOS, DANSS) ruled out oscillations in a lot of space suggested by the Flux Anomaly.

  - Crucial phase space remains unaddressed, including a positive claim by Neutrino-4

- New neutrino/nuclear modeling/ measurements support another explanation: bad flux predictions.

  - Sterile oscillations are perfectly compatible with this scenario, but at smaller (0-10%) amplitudes

Akindele et al, hep-ex[2203.07214]

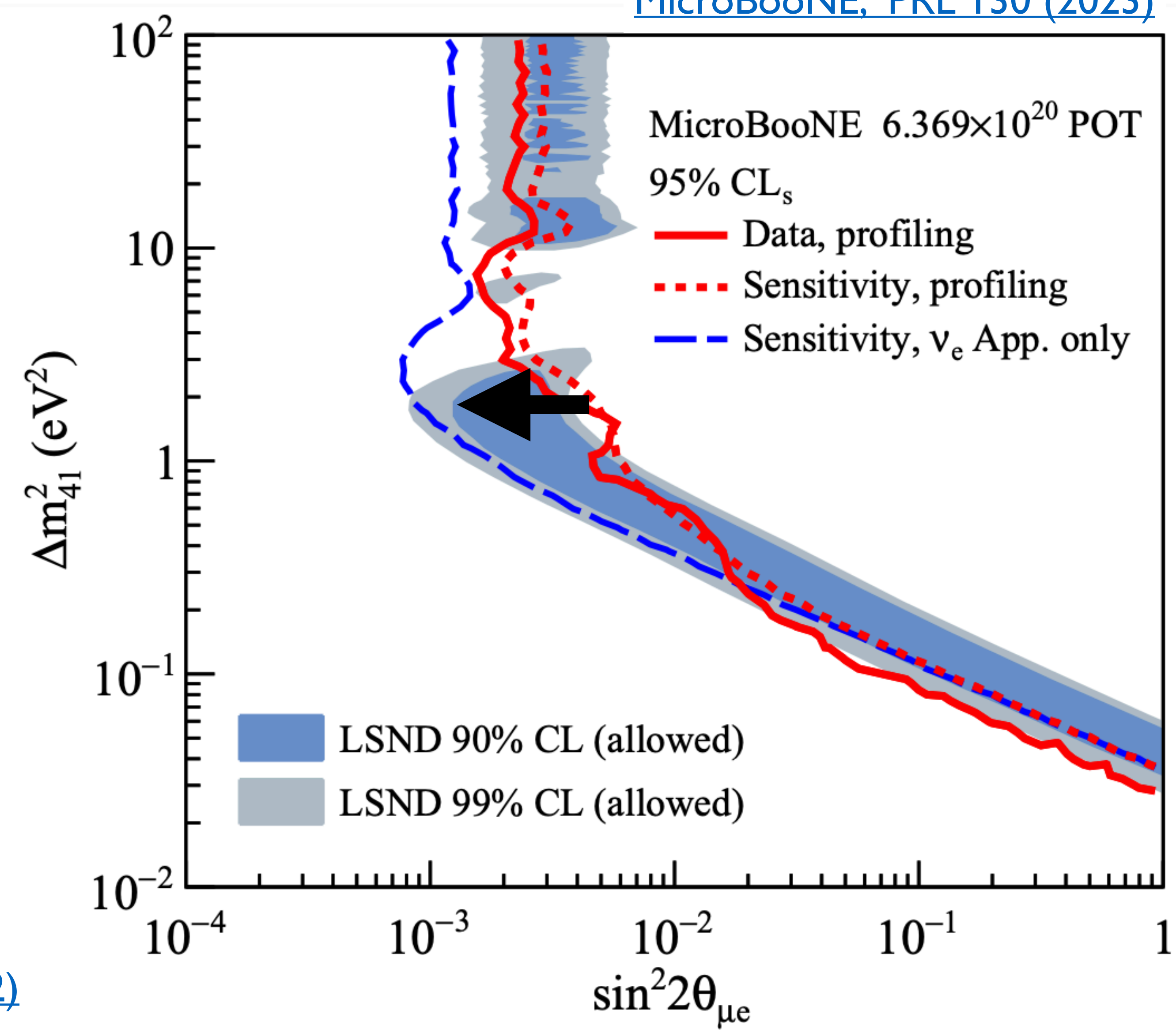


Non-Standard Oscillations: Anomalies

- The three other short-baseline anomalies remain unexplained: Gallium, LSND, and MiniBooNE

- Many pheno explanations impact reactor signatures
  - `3+1' sterile picture, for example
  - 'Non-vanilla' models too: 3+1+NSI, 3+1+decay, others
- A key to unravelling/excluding BSM causes: dataset diversity
  - MeV and GeV; muon and electron; appearance and disappearance
  - Example: Testing MiniBooNE with MicroBooNE data Arguelles et al, PRL 128 (2022)

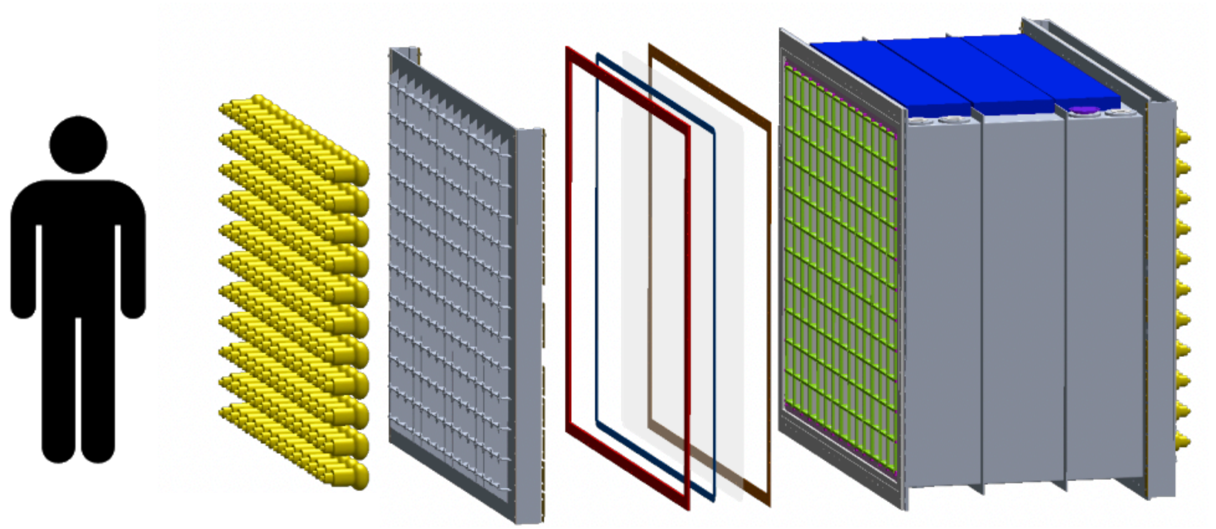
MicroBooNE, PRL 130 (2023)

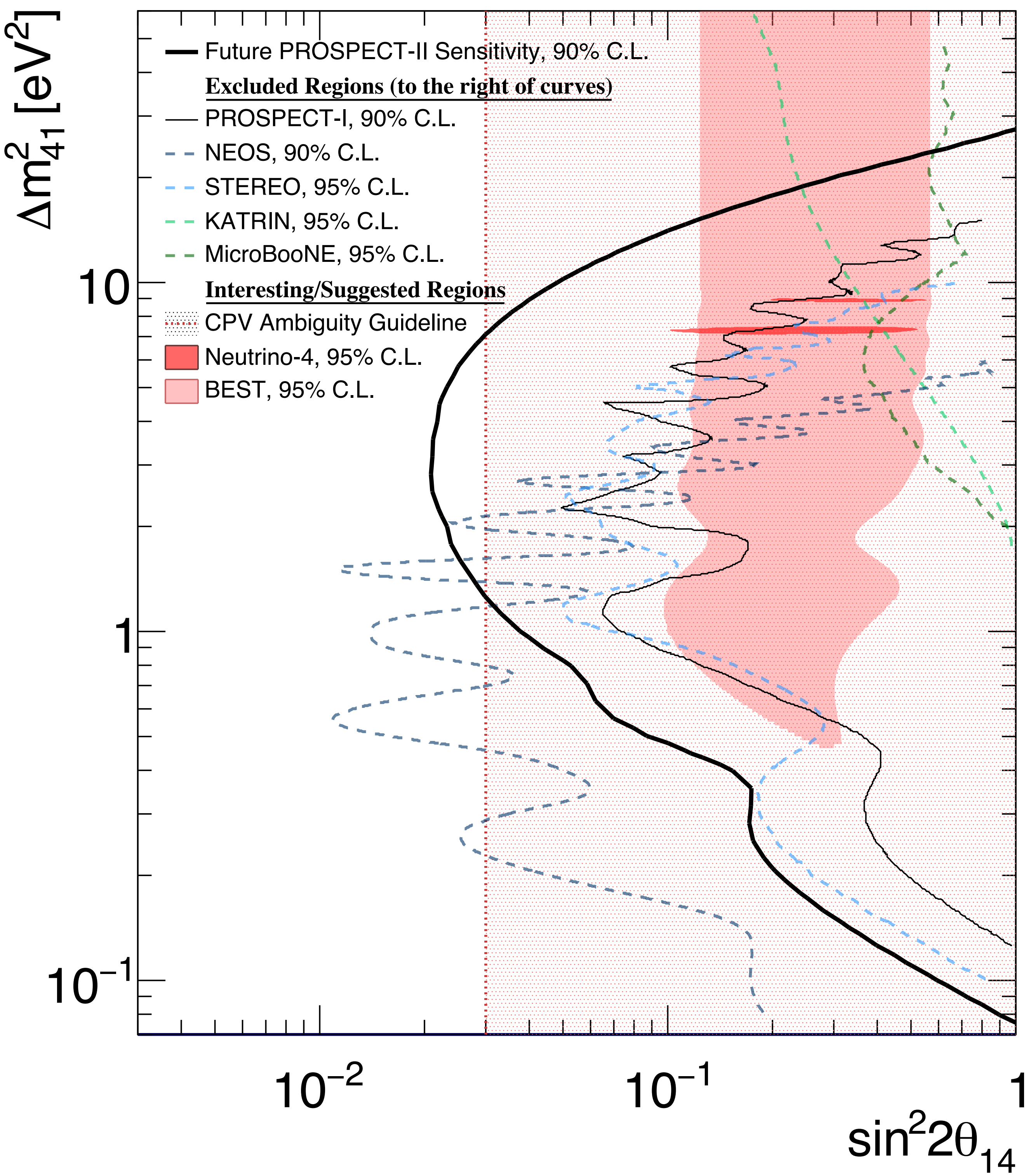


- Short-baseline reactor experiments play a unique role in an integrated global effort to understand these anomalies.

Non-Standard Oscillations: Future Aims

- Near-future reactor experiments can address much of the remaining ‘interesting’ oscillation space in the next P5 period.
- Example: PROSPECT-II
  - In 1 year, clearly address claims of Neutrino-4 at high mass splitting
  - Cover all remaining Gallium Anomaly, RAA oscillation space below ~10 eV^2
  - Pin down electron disappearance to the few percent-level below ~10 eV^2, benefitting anomaly and long-baseline oscillation interpretations

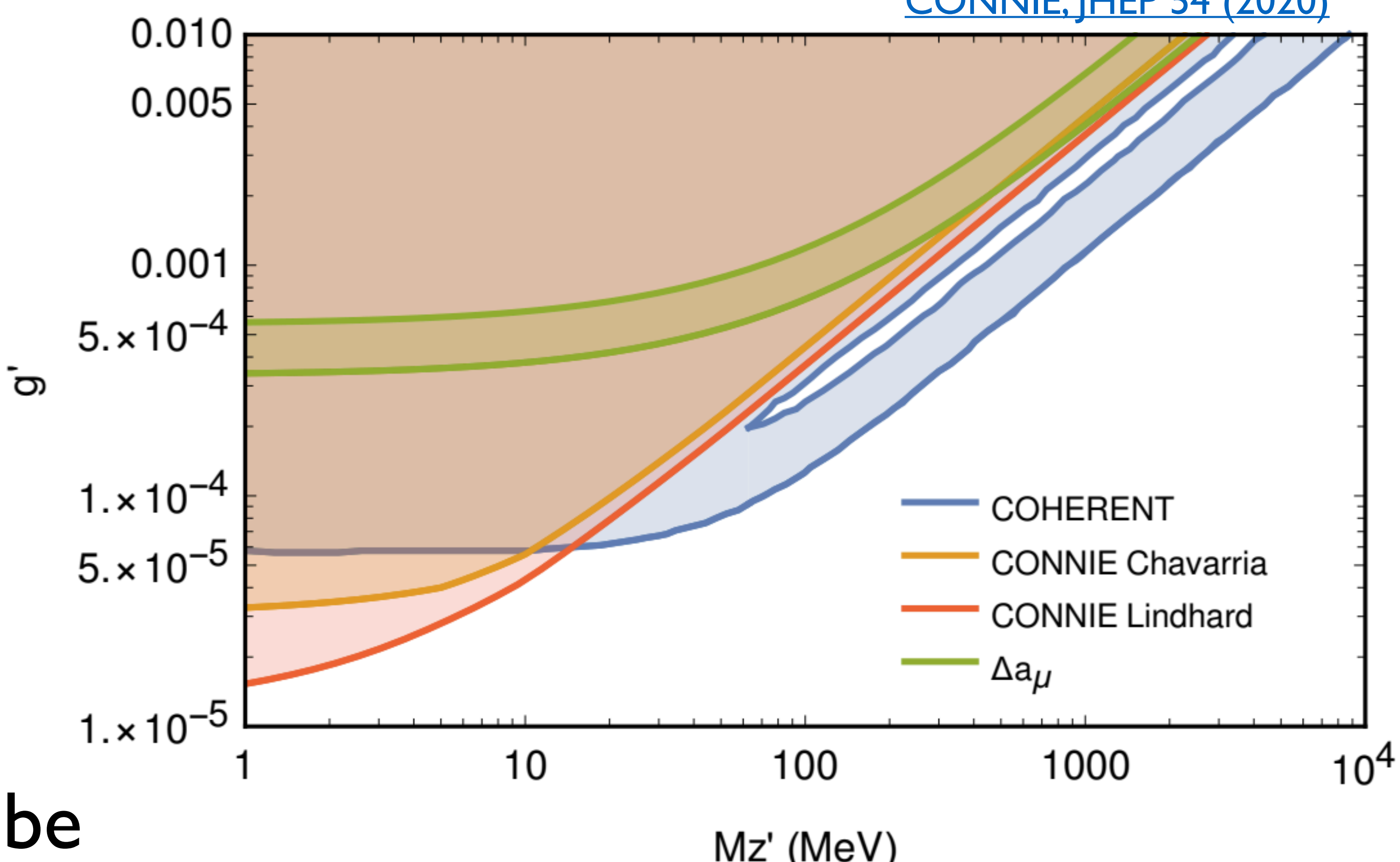




BSM Physics: Progress and Aims

- Reactor-based experiments, just like beam experiments, have hopped aboard the Neutrino BSM train.
- Many reactor BSM signatures are being explored; scope will broaden in future, coupled with advancing detection technology
  - CONNIE: New BSM couplings observable in coherent neutrino-nucleus scatters ('reactor CEvNS')
  - PROSPECT: Boosted dark matter
  - TEXONO: reactor-produced millicharged particles

CONNIE, JHEP 54 (2020)

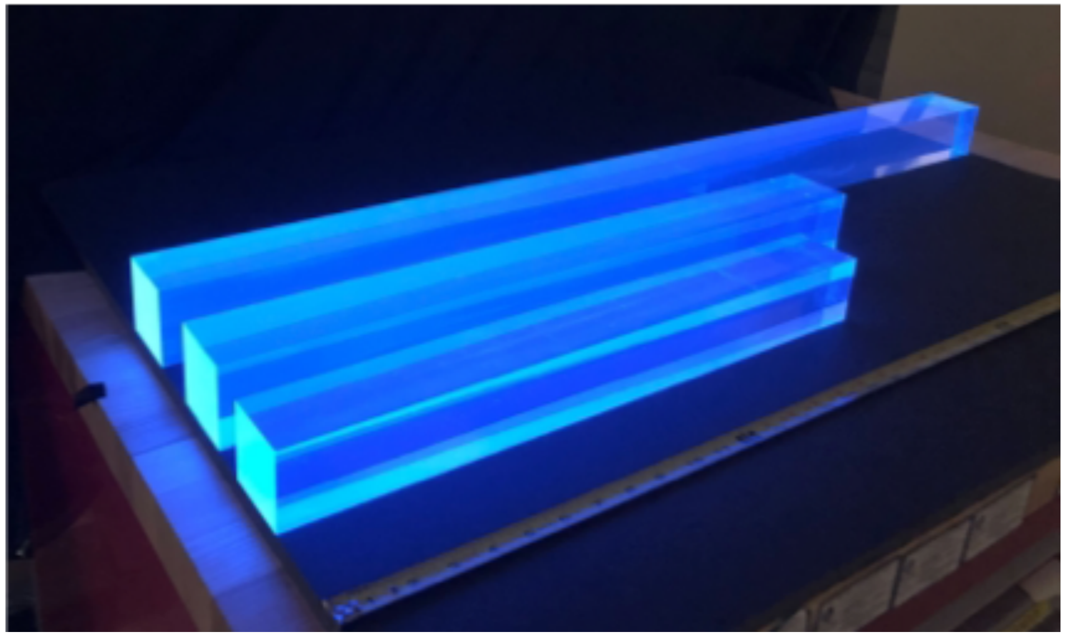


- Future sensitivity may be limited by reactor flux knowledge, can be solved by other reactor experiments (PROSPECT-II, etc.)

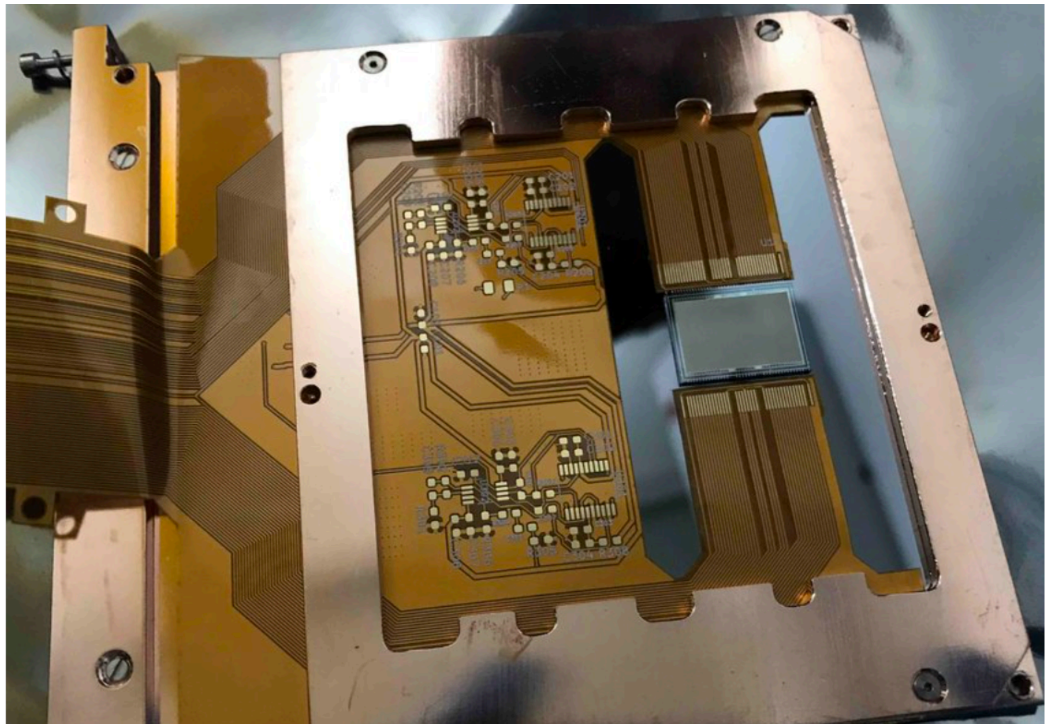
Reactors and Detector R&D

- Reactor neutrino experiments are drivers of broadly-useful particle detection and QIS-relevant technology
    - Short-baseline reactor experiments (PROSPECT, MAD, CHANDLER): technology for reactor monitoring, neutron detection applications, like Li-doped PSD scintillator
    - Reactor CEvNS experiments (RICOCHET, CONNIE, MINER, etc.): QIS-relevant tech/infrastructure/expertise, such as cryogenic detector facilities, operations, readout, multiplexing, etc.

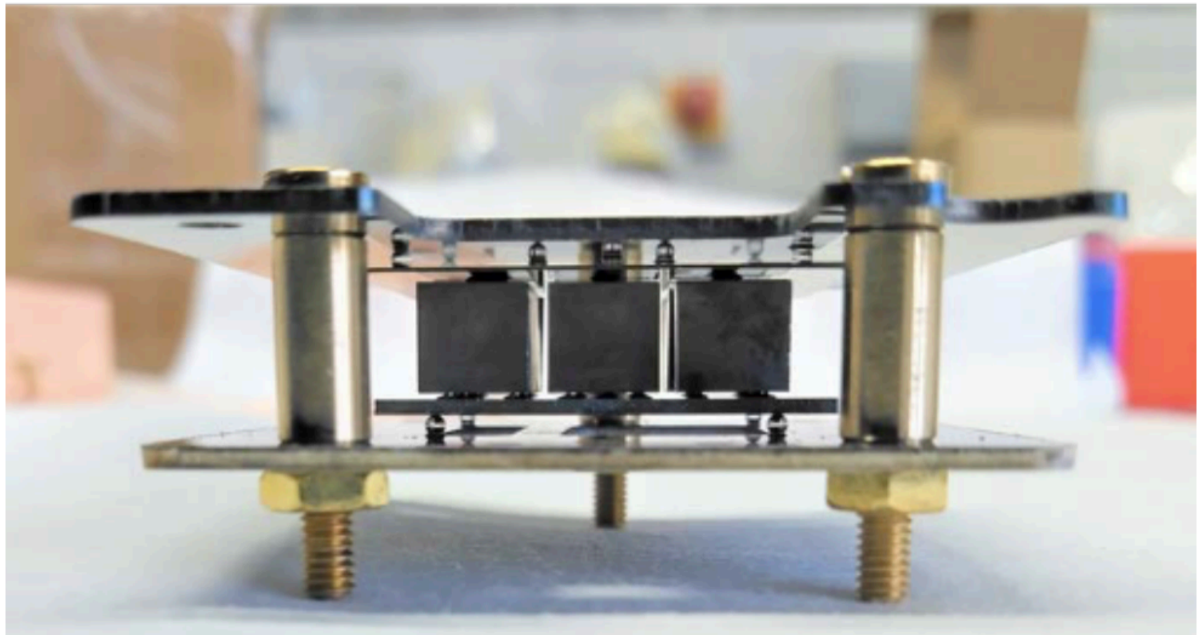
[Li-doped PSD scintillator bars at LLNL]



[CONNIE: low-threshold ionization detectors]



[NUCLEUS: cryogenic phonon detectors]

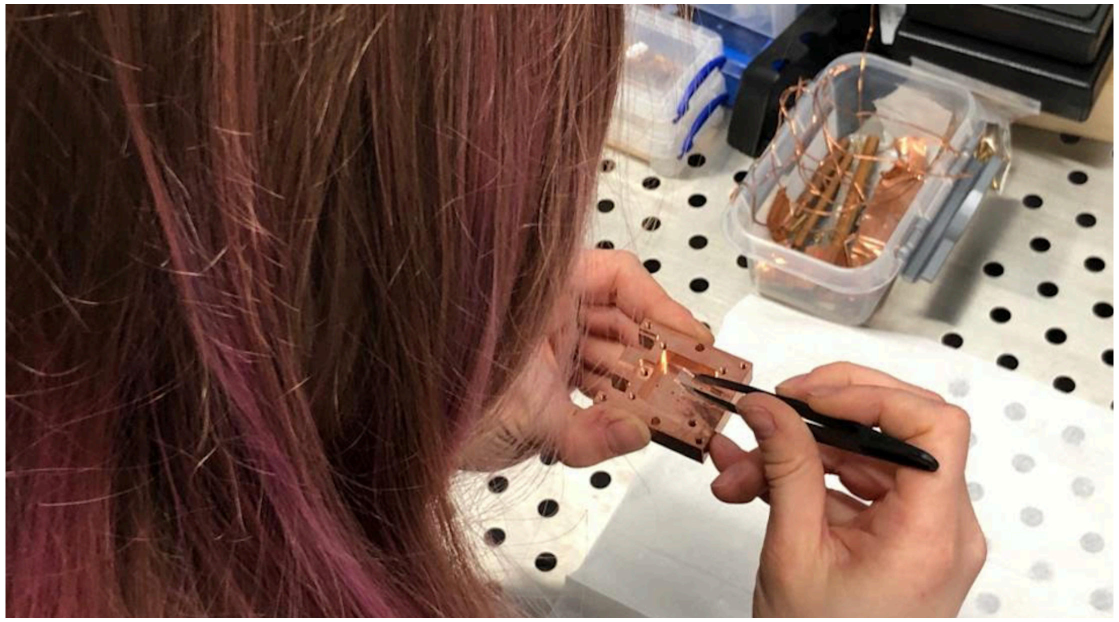


Reactors and Workforce Development

- Current and future reactor experiments provide ideal timescales and experiences for training early-career scientists
  - Short, near-term timescales
  - Range of sizes: from ‘tabletop’ to ‘kilotons’
  - One student, many skills: hardware, software, analysis

[PROSPECT's Hands-On Construction]

[MINER team at TAMU's TRIGA reactor]

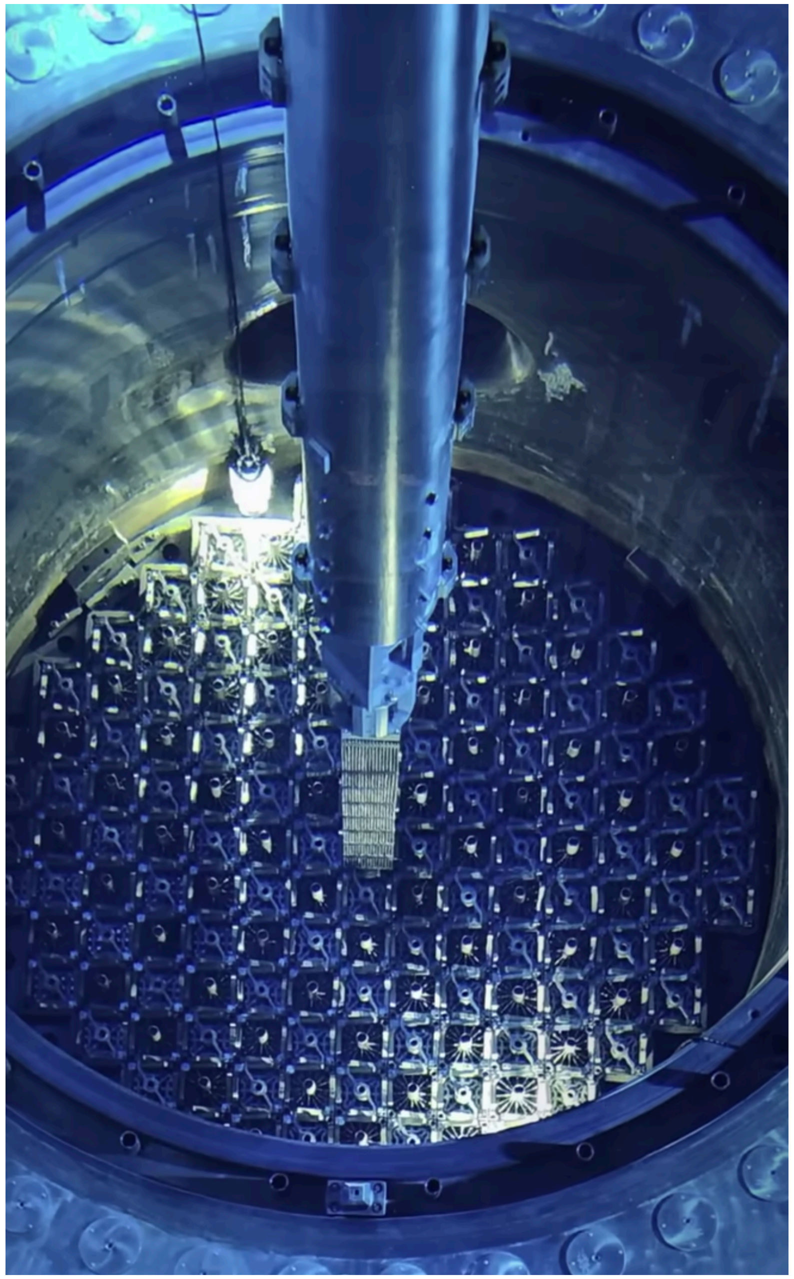


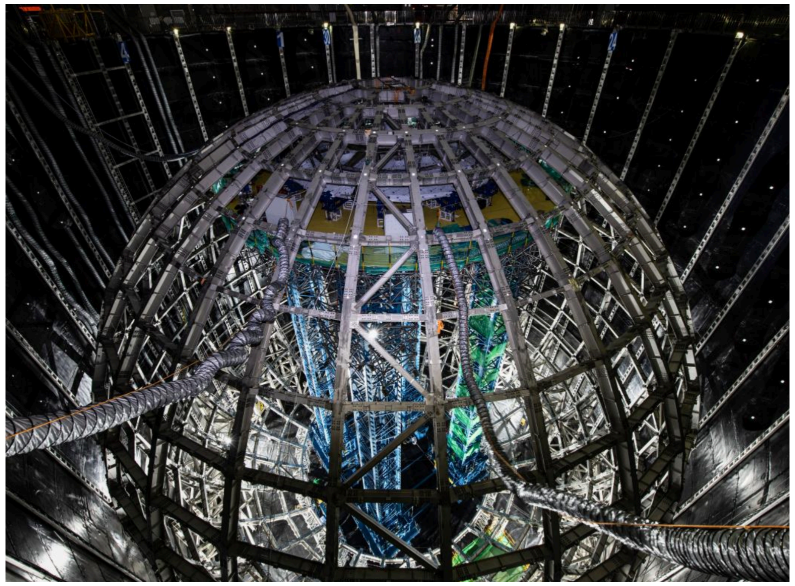
Tabletop detector prep for NUCLEUS (courtesy R. Strauβ)

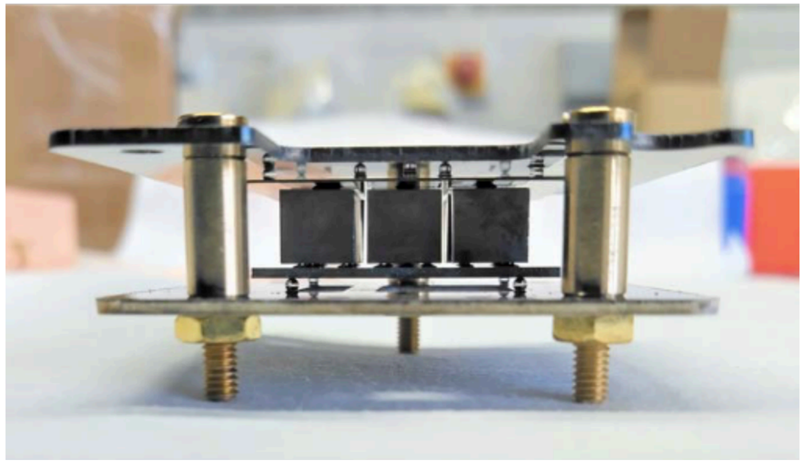
Summary

- Nuclear reactors emit antineutrinos with unique flavor, energy, and operational attributes.
- Reactor neutrino experiments are an essential piece of a global effort to achieve precision tests of lepton flavor mixing and complete understanding of long-standing neutrino anomalies.
- Many reactor experiments can be initiated, run, and completed within timescales/budgets associated with the next P5 period.
- Reactor neutrino efforts are drivers of applied and QIS-oriented technology development in particle physics.
- Spanning scales from tabletop to kiloton, reactor efforts offer valuable near-term workforce development opportunities.
- More questions? See the Snowmass 2021 Reactor Whitepaper

Thanks!

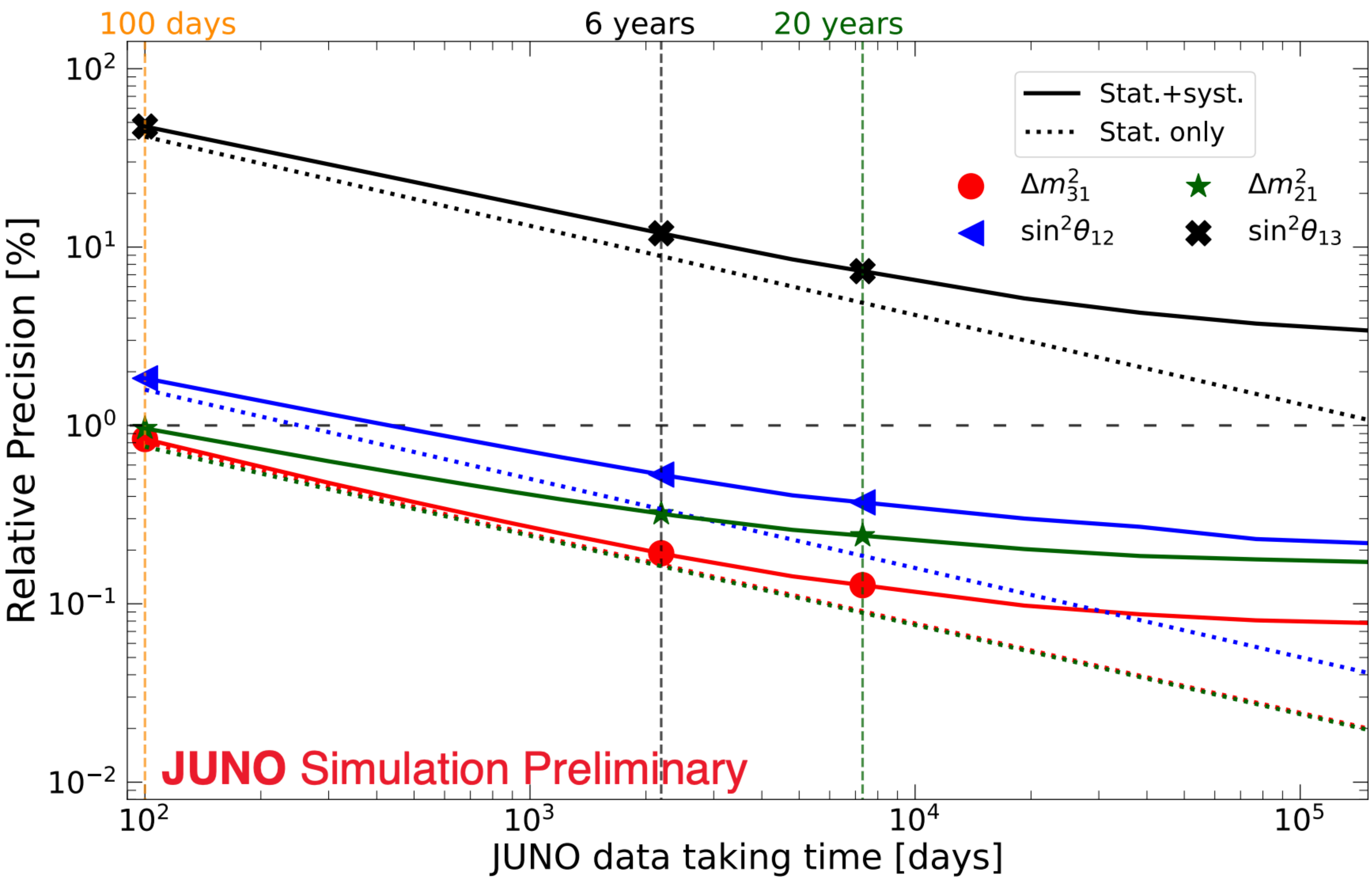






Backup

JUNO Physics Delivery vs. Time

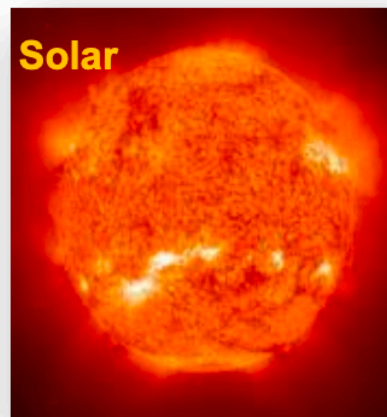


JUNO Physics Topics

A multi-purpose observatory

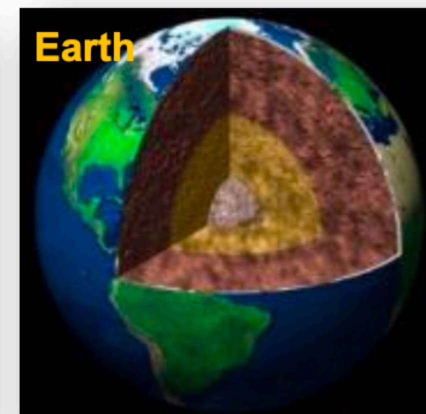
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

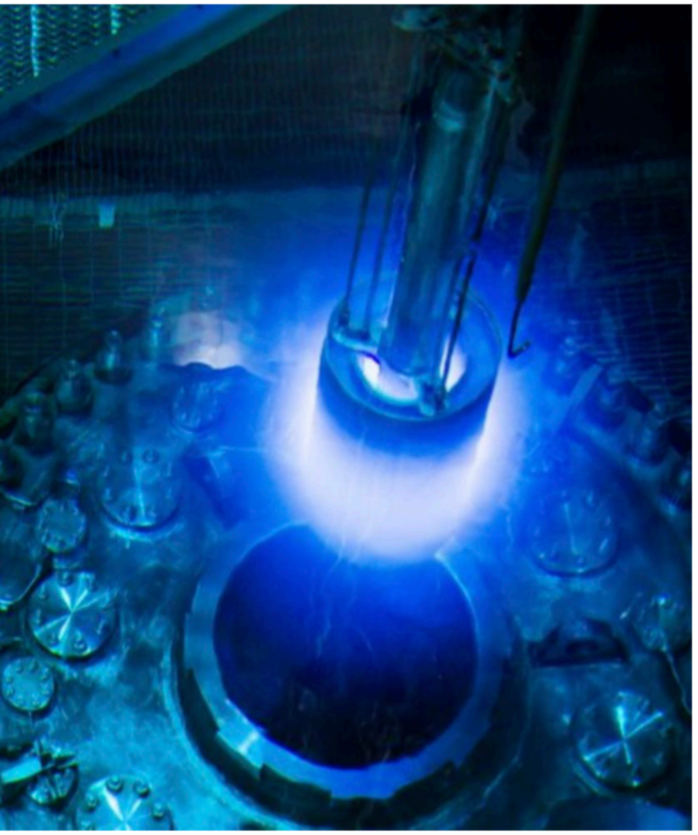
IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

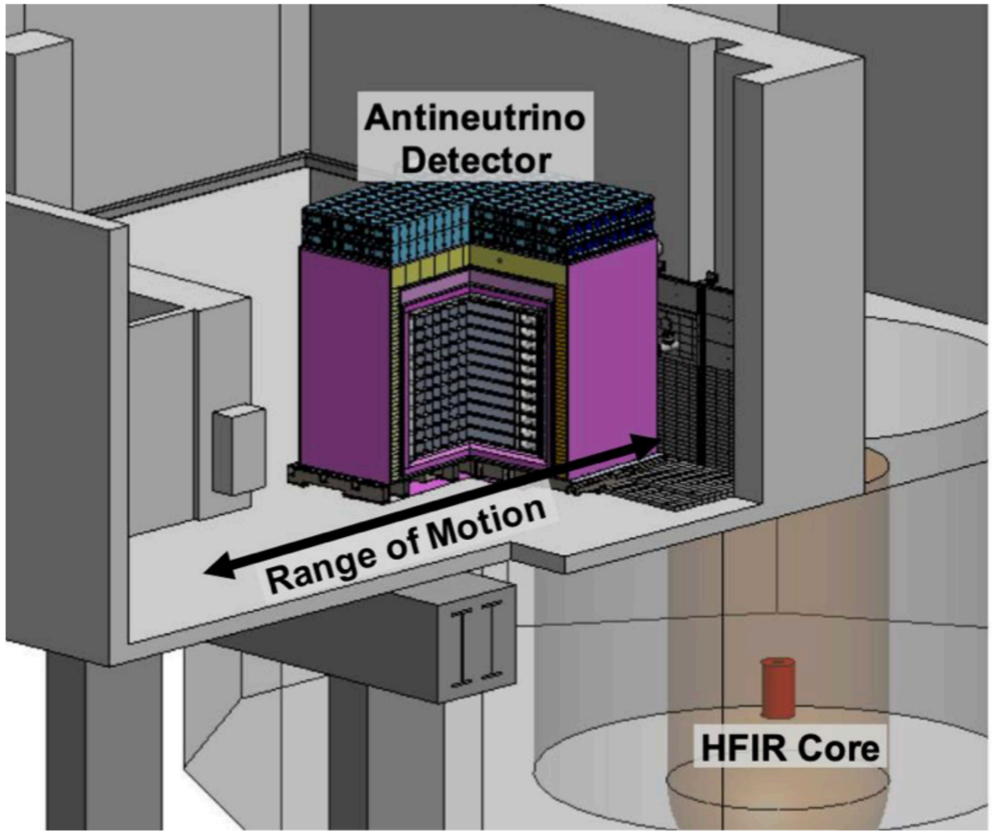
What Is PROSPECT?

What Is PROSPECT?

- PROSPECT is the world's first precision on-surface reactor neutrino experiment
- A multi-ton segmented, Li-doped PSD-capable liquid scintillator detection instrument
- Situated at the compact, highly ^{235}U-enriched High Flux Isotope Reactor (HFIR) at ORNL



A HFIR Core



The PROSPECT Layout

PROSPECT-I at HFIR, 2018

PROSPECT-II Design

PROSPECT-II Design and Run Plan

- **PROSPECT-II is shovel-ready: demonstrated technology, modest design updates, rapid production.**
- **Like PROSPECT-I, PROSPECT-II can be fabricated and deployed in roughly 1 year: July 2023 - July 2024**
- **PROSPECT-II can capture ~13 HFIR cycles through 2026, and have x10 statistical power of PROSPECT-I**